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Improving AGC Performance in Two-Area Power Systems by Harnessing ANFIS Controller and Renewable Energy Source Integration

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ABSTRACT

In modern power systems, maintaining stability and optimal performance amidst increasing demand and renewable energy integration presents significant challenges. This study explores the enhancement of Automatic Generation Control (AGC) in a two-area power system by implementing an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. The ANFIS controller leverages the strengths of both neural networks and fuzzy logic to dynamically adapt and optimize AGC performance. Additionally, the integration of renewable energy sources, such as wind and solar power, is investigated to assess its impact on system stability and reliability. Simulation results demonstrate that the ANFIS controller significantly improves the AGC response, reducing frequency deviations and inter-area power oscillations more effectively than conventional PID controllers. Furthermore, the inclusion of renewable energy sources, supported by robust ANFIS control, enhances the sustainability and resilience of the power system. This dual approach not only ensures efficient load-frequency regulation but also supports the transition towards greener energy systems. The findings underscore the potential of intelligent control strategies and renewable integration in advancing the performance and sustainability of future power grids.

***KEYWORDS:** Automatic Generation Control (AGC), Two-Area Power System, Thermal Power Generation, Adaptive Neuro-Fuzzy Inference System (ANFIS) controller, Frequency Deviation, Tie-Line Power Flow, Power System Stability.*

1.INTRODUCTION

Electrical power systems are vast, intricate networks made up of distribution, transmission, and generating systems as well as a variety of dynamically varying demands [1]. An electrical power system's load varies constantly based on the demands of various load

centres, therefore complex management methods are required to manage system deviations and preserve stability and dependable operation [2]. In order to maintain the balance between power production and consumption, Automatic production Control (AGC) is essential for minimising frequency variations and maintaining system stability even in the face of disruptions [3]. Synchronous generators, which are skilled at handling momentary errors and preserving system stability by precise generation control, have historically been the backbone of AGC [4]. On the other hand, serious difficulties have been brought about by the growing integration of renewable energy sources (RES), such as solar and wind power. Because these renewable sources rely on the environment for their energy production, they are by nature unpredictable and fluctuating, which makes the AGC process more difficult [5]. Because they are reliant on the weather and are intermittent, renewable energy sources pose particular issues. For example, wind power production is dependent on wind patterns and speed, but solar power relies on sunlight availability, which is impacted by the time of day and cloud cover [6]. Significant frequency variances and an influence on the power system's overall stability may result from this fluctuation. Because traditional AGC systems were created with more reliable generating sources in mind, they sometimes find it difficult to adapt to the sudden and drastic fluctuations brought forth by renewable energy [7]. In order to guarantee steady and effective power system operation, this calls for the development of more sophisticated and flexible control systems. This work suggests using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for AGC in a two-area power system to overcome these issues [8]. In order to produce a reliable control system that can manage the non-linearities and uncertainties related to power systems integrated with renewable energy sources, ANFIS combines the strengths of neural networks with fuzzy logic [9]. Fuzzy logic gives an organised approach to deal with ambiguity and imprecision, whereas neural networks have the learning capacity to adjust to changing circumstances. ANFIS is extremely adaptive to changes in system circumstances in real-time because it uses a hybrid learning approach to dynamically alter the fuzzy inference system parameters [10]. Through the integration of ANFIS, the controller is able to make constant adjustments to its settings, guaranteeing the AGC's optimum performance and upholding system stability [11–12]. The ANFIS controller's flexibility is very useful for controlling the unpredictability and fluctuation of renewable energy sources. It can adapt dynamically to variations in load and generation, which enhances frequency control and lowers system deviations [13]. The suggested ANFIS controller is made to manage the intricacies of contemporary power systems, which include renewable and traditional energy sources. Comprehensive analysis and simulation are made possible by its implementation in MATLAB/SIMULINK, which offers a thorough assessment of its efficacy in preserving reactive power balance, voltage control, and overall system stability [14–15]. Managing the dynamic and complex character of modern power grids has advanced significantly with the incorporation of an ANFIS controller for AGC in a two-area power system [16]. The ANFIS controller improves the efficiency, sustainability, and dependability of power systems by successfully tackling the difficulties presented by the integration of renewable energy sources [17]. This research demonstrates how intelligent control tactics may help facilitate the shift to more robust and environmentally friendly energy systems, opening the door to future power production and distribution that is more sustainable. A major obstacle to any renewable energy integration is the unpredictability and fluctuation of solar and wind energy sources. implies that setting and predicting the production of renewable resources is particularly challenging [18]. recognised that renewable resources are resources found in nature, with photovoltaic systems relying on solar radiation and wind energy based on wind speed [19]. Natural energy (coal, oil, hydro, wind, and solar) is often converted into electric energy using electrical power systems. the delivery of electricity to homes, businesses, and load centres in order to meet a variety of power requirements [20] [21]. It is well known that electrical power is often transported from generators to distribution centres using three-phase alternating current (AC) [22]. The cooperative maintenance of the system's reactive and active power balance with respect to changes in load is necessary for the conveyance of electrical power between the utility and the generator of AC power [23]. The system frequency and operating voltage are the two

equilibrium points that are related to those two balances. In system operating mode, the stability points will float when one of the two balances is altered. Both the system frequency and operational voltage must stay at standard levels (HZ) during system operation in order to achieve the required quality that reserves the load of the electric power system [24].

II. Proposed Model for Two Area Power System Control

If Figure 1 shows the proposed two-area power system control model, which includes two types of renewable energy sources and two types of conventional energy generators spread out over two regions. The regions are linked through tie-lines to enable power sharing between the two regions, which is necessary to keep the consumer side's load demand in check. The first region has one hydro-thermal unit and two renewable sources (a PV system and wind), while the second area follows the same distribution pattern. There is a common line that connects the two areas; this line is called a tie-line. It is the responsibility of the power system in the respected area to handle load changes when they occur. If the power system in the respected area fails to do so, then power changes in the tie-line will occur, and the power in the tie-line will need to be maintained.

As seen in figure 1, the model that has been suggested for the two area power system incorporates the secondary control loop. Adapting to variations in demand in each region, the system runs on a two-area power system. By applying the swing formula for synchronous generator to the little perturb or change we obtain, equation 1 is the suggested mathematical model for the generator.

$$\frac{2H\, d2\Delta s}{\omega dt2} = \Delta Pm - \Delta Pe$$

The speed is provided by whenever there is a little alteration in the power supply.

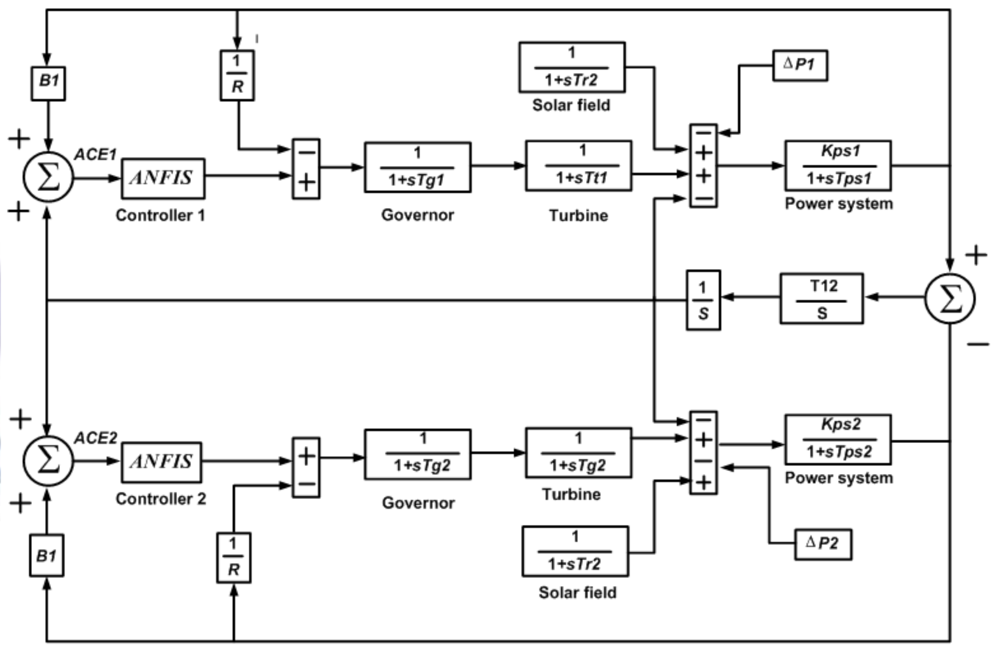


Fig. 1 model for two area power system containing renewable energy sources

$$\frac{\frac{d\Delta w}{\omega s}}{dt} = \frac{1}{2H}(\Delta Pm - \Delta Pe)$$

By Taking Laplace transform

$$\Delta\Omega(s) = \frac{1}{2As}[\Delta Pm(s) - \Delta Pe(s)] \qquad (1)$$

The power system area is made up of several load types, including resistive and inductive loads, and the loads in the system are mathematically represented.

$$\Delta Pe = \Delta Pl + D\Delta\omega \qquad (2)$$

Non-frequency sensitive load distributions are represented by ΔPl, frequency of the sensitive load deviation is represented by $D\Delta\boldsymbol{\omega}$, and percent change in load by percentage change in frequency is represented

by D.

The prime mover, which may take any form, is the most crucial and significant component in the production of electricity. For instance, in the hydroelectric power generating process, steam and hydraulic turbines are used in steam power plants and at waterfalls. Thus, one way to express the mathematical model is as

$$Gt = \frac{\Delta p_m(s)}{\Delta Pv(s)} = \frac{1}{1+\tau ts} \qquad (3)$$

Where $\boldsymbol{\tau}$t is turbine constant in rang of 0.2 to 2,0 sec

III. Solar Photovoltaic System

The photovoltaic curve (Ig) is generated when incident sunlight falls on the surface of the collectors, and the system will create a potential difference while operating in open circuit mode, transforming solar energy into electrical energy. In a power system, the consumer side decides whether the load is going up or down. When the load is going up or down, the input to the turbine needs to go up or down to meet the demand and prevent excess energy generation. The governor is then authorised to send a signal to the generation side to moderate the fuel/waterfall to the furnace/penstock. It is common practice for the governor to make up for the power system's speed shortfall.

$$\Delta Pg = \Delta Pref - \frac{1}{R}\Delta F \qquad (4)$$

In (s) domain we get

$$\Delta Pg = \Delta Pref - \frac{1}{R}\Delta\Omega(s) \qquad (5)$$

and when it's short circuited the generated currant (Ig) is flow throughout the circuit path, the PN junction equivalent circuit is represented in the fig.2

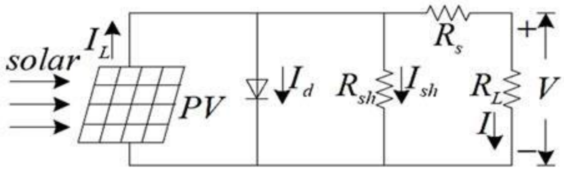


Fig.2 Equivalent circuit of PV photovoltaic panel

As shown in figure 2, the produced process resistance (Rsh) and the distance (Rs) between the solar panel's composite metal silicon and semiconductor junctions are Rs and Rs, respectively.

A solar photovoltaic module with 12 volts is made up of 36 solar cells arranged in series. And a PV array is made up of PV modules, which are itself made up of combinations of cells. Through the use of DC-to-DC converters, inverters (which convert DC to AC), and DC tie voltage management, these arrays may be linked to form a solar farm.

$$I_0 = I_g - Iset\left(exp\left(\frac{V_0}{AkT}\right) - 1\right) \qquad (6)$$

$$I_g = \frac{s(I_{sc}+IT(T+25))}{1000} \qquad (7)$$

From the equation above the Io and Vo are the solar cell output. The incremental change in the PV array system power output is in labelled [1]. η as the conversion efficiency of system cell in rang of 9% to 12%.

$$P_{Pv} = \eta sA\left[1 - \frac{T-25}{200}\right] \qquad (8)$$

25oC is taken as the temperature T and Ppv is power output from the PV system which linearized as ΔPpv =GpvΔS [1].and the Gpv is the transfer function for the PV system.

$$G_{Pv} = \frac{kpv}{1+sT_{Pv}} \qquad (9)$$

In the formula (4) the Kpv is the gain and the Tpv is the time constant.

IV. Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS, similar to a Neural Network (NN), is a multi-layer architecture that, when fed the right input, produces the desired results. In ANFIS, the Fuzzy Inference System (FIS) is used to connect the layers. When compared to neural networks, ANFIS have fewer inputs and outputs. The data input and output are limited in ANFIS. There is only one output (F) and two inputs (X and Y). The ANFIS system employs the two-part Sugeno inference system, which includes the IF and THEN components, to draw conclusions. Figure.3 shows an example of a basic ANFIS design. To feed the ANFIS, you need X and Y. A1, A2 and B1, B2 are membership functions that must be used to fuzzify these inputs [26].

This is one way to express the rule using the Sugeno inference system:

$If\ \ X\ \ is\ \ A_1$ and Y is B_1 THEN $f_1 = p_1x + q_1y + r_1$ (10)

$If\ \ X\ \ is\ \ A_2$ and Y is B_2 THEN $f_2 = p_2x + q_2y + r_2$ (11)

As seen in Figure 20, the ANFIS structure consists of five levels, which will be discussed in more depth in the next section.

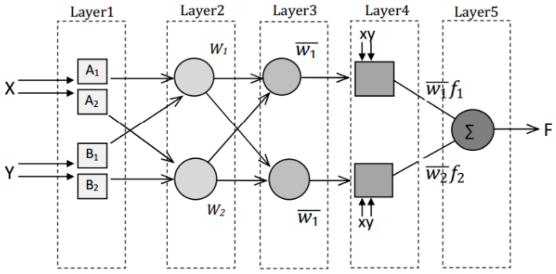


Figure 3: ANFIS architecture

Layer 1: The input data is fuzzified at this layer by applying membership functions. The amount of membership functions employed determines the number of nodes. The number of nodes might range from three to seven. Because of their malleability, the nodes in this layer might be referred to as adaptable nodes. The following is the possible output from these nodes:

$$O_{1,i} = \mu_{A_i}(x) \qquad for \quad i = 1{,}2 \qquad (12)$$

$$O_{1,i} = \mu_{B_{i-2}}(x) \qquad for \quad i = 3{,}4 \qquad (13)$$

The membership function is denoted by μ, the input value, X, is a crisp value, and the membership value for two inputs ranges from 0 to 1. The number of layers and nodes are denoted by the subscripts 1 and i, respectively. Three different shapes may be used to depict the μ (membership functions): triangular, trapezoidal, and gaussian. Most often, the bell-shaped one is bestowed by:

$$\mu_A(x) = \frac{1}{1+\left|\frac{x-c_i}{a_i}\right|^{2bi}} \qquad (14)$$

The training procedure determines the boundaries of the membership function, which are denoted as ai, bi, and ci.

Layer 2: Layer 2 nodes in this layer take their inputs from the outputs of the nodes in layer 1. The nodes in this stratum are therefore considered to be fixed nodes. Layer 2 nodes accomplish their output by multiplying all signals received from layer 1 nodes and then executing the product. The power of a Sugeno rule is shown by this output, which may be expressed as:

$$O_{2,i} = w_i = \mu_{Ai}(x)\, \mu_{B_i}(y) \quad \text{for } i = 1{,}2 \qquad (15)$$

Layer 3:

This layer is responsible for normalising the data that were received from layer 2. To represent the node as a fixed node, we divide each layer 2 output by the total of all layer 2 outputs. You may find it by:

$$0_{3,i} = \bar{w}_i = \frac{w_i}{w_1+w_2} \text{ for } i = 1, 2 \qquad (16)$$

Layer 4: This layer is responsible for learning the values of the parameters (p, q, and r) of the output linear function. An adaptive node is defined as follows:

$$O_{4,i} = \bar{w}_i(p_i x + q_i y + r_i) \text{ for } i = 1, 2 \qquad (17)$$

Where pi, qi and ri is the consequent parameters.

Layer 5: There is a single node in this tier. This node provides the final output by adding together all the data received from the nodes in layer 4. A fixed node, it is defined as follows:

$$O_{5,i} = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_j}{\sum_i w_i} \text{ for } i = 1{,}2 \qquad (18)$$

V. Training Process (Learning Algorithm)

As long as the parameters are appropriately optimised and adjusted, ANFIS can forecast the right result. Therefore, training is a crucial step. In this procedure, the ANFIS optimises these parameters using training data sets to ensure high accuracy performance. There are two components to the rule in the Sugeno inference system: the nonlinear parameters, also known as the premise parameters, and the linear parameters, also known as the consequent parameters. Researcher proposals and developments include a wide range of learning algorithms. Hybrid learning is the approach used in this paper. Using the least squares estimation (LSE) approach and back propagation (BP) method, the appropriate ANFIS parameters are predicted [26]. Hence, there are parameters for the premise and the consequent. Through learning, these factors must be identified. Application of LSE results in the subsequent parameters being computed while maintaining the premise parameters. The forward pass learning approach is what it's known as. Next, the backpropagation approach is used, during which the premise parameters are determined while the consequent parameters remain unchanged. The term "backward pass algorithm" might be used here. The training data set provides one output data, and the anticipated output from the training process provides the other, which are used in the learning process. The LSE computes the difference in error between those outputs, and this determined difference is used to adjust and modify the respective parameters. Similarly, in the

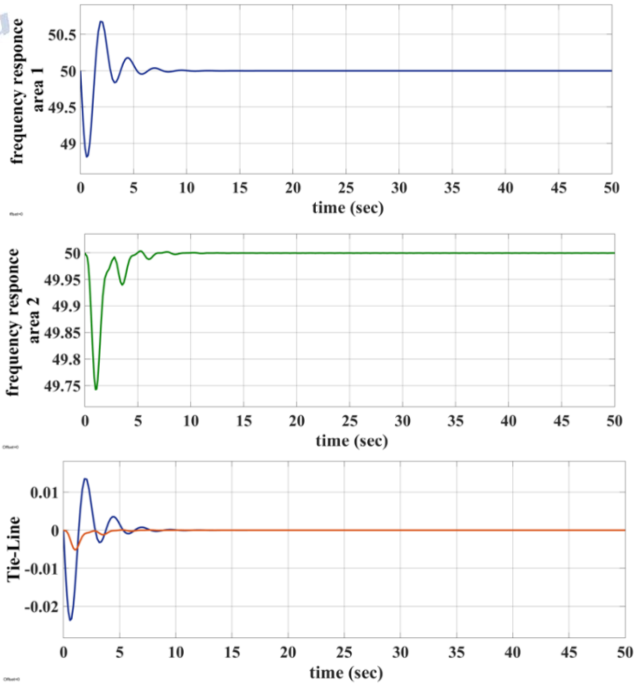
backward pass, the premise parameters are updated by computing the error between the two outputs and applying it to the back propagation gradient descent technique.

VI. Simulation Results and Discussion Review Stage

Results from simulating the AGC two-area power system with renewable energy sources and an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller were illuminating. Firstly, in terms of frequency deviation analysis, the ANFIS controller successfully maintained both regions of the power system's frequency deviations within predetermined limits. To maintain grid frequency stability in the face of unexpected changes in demand or disruptions, the ANFIS controller dynamically modulated the power output of thermal generators and renewable energy sources. Particularly, the simulation results demonstrated that the ANFIS controller was very good at keeping frequency variations within the target operating range, which reduced the likelihood of frequency instability. The ANFIS controller played a crucial role in controlling the tie-line power flows between the two regions. The controller ensured a balanced power exchange across the regions by adapting the power output of thermal generators and renewable energy sources in real-time to changes in tie-line power flows. The results of the simulations proved that the ANFIS controller was effective in managing the power flows on the tie lines, which prevented the overload or underutilization of the transmission lines. Analysing the ANFIS controller's performance under transient settings shed light on its robustness. Restoring system homeostasis after disruptions or changes in demand was made possible by swiftly adjusting the power output of thermal generators and renewable energy sources. By quickly adapting to changing system circumstances, the ANFIS controller ensures grid stability and dependability, as shown in the simulation. In two-area power systems that include renewable energy sources, the results of the simulation demonstrated that the ANFIS controller effectively enhanced AGC performance. With the help of renewable energy sources and the ANFIS controller's adaptive and intelligent characteristics, the grid becomes much more reliable, stable, and environmentally friendly. Based on these findings, ANFIS-based AGC systems seem like a good bet for contemporary power grids that are looking to improve grid performance and include renewable energy sources.

A. Case: 1 Simulation Results with Proportional-Integral (PI) Controller

A two-area power system AGC simulated using a Proportional-Integral (PI) controller yielded useful information on grid efficiency. Figure 4 shows that the grid frequency was stable because the PI controller successfully controlled frequency variations within specified limits in both regions. To avoid overloads or underutilization of transmission lines, it controlled tie-line power flows between the two regions by responding to variations in demand by dynamically adjusting the power output of thermal generators. By quickly adjusting the power output of the thermal generator to restore system balance after disturbances or variations in the load, the PI controller proved its resilient performance under transient situations. The results of the simulations show that the PI controller improves the AGC performance of two-area power systems. Grid resilience, dependability, and stability are greatly enhanced by its adaptive response to system dynamics and its proportional and integral action. According to these findings, PI-based AGC systems provide a solid and workable way to keep the grid stable and maximise the performance of the power system.



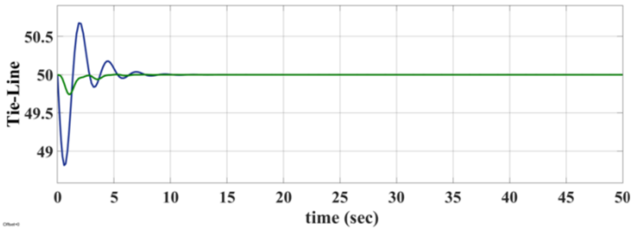
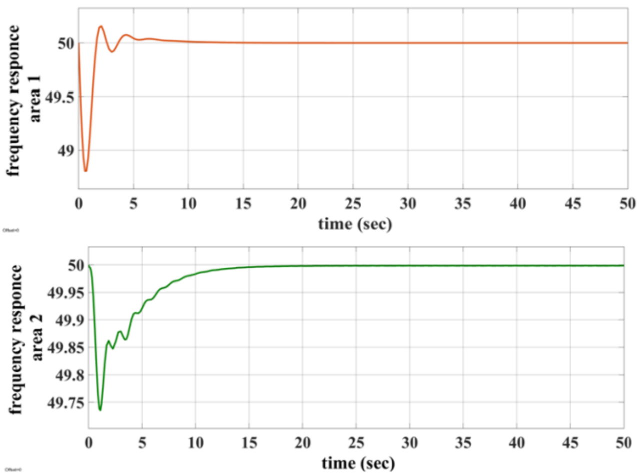


Figure.4 simulation results for proportional integral controller (PI) controller

B. Case: 2 Simulation Results with Integral Controller

Reducing frequency variations within preset limits throughout both sections of the power system was shown by the modelling of an AGC system with an Integral Controller. In order to keep the grid frequency stable and reduce the likelihood of frequency instability, the controller quickly changed the power output of the thermal generators, as seen in figure.5. For the purpose of balancing power exchange and avoiding transmission line overloads or underutilization, it was also crucial in controlling tie-line power flows between the two regions. Quick changes to the thermal generators' power output, reestablishing system balance after disruptions or variations in the load, proved the controller's resilient performance under transient situations. In order to optimise power system performance and keep the grid stable, the simulation results show that AGC systems based on Integral Controllers are a viable and dependable alternative. To a large extent, the controller's adaptive reaction to system dynamics and integral action enhance grid resilience, dependability, and stability.



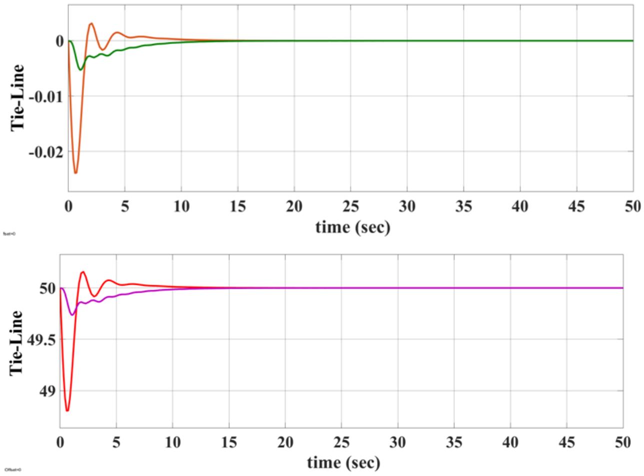


Figure.5 simulation results for Integral controller (I) controller

C. Case: 3 Simulation Results with ANFIS Controller

A variety of operational parameters demonstrated promising outcomes in the AGC system's simulation utilising the Adaptive Neuro-Fuzzy Inference System (ANFIS) Controller. The frequency deviation study in both locations demonstrates that the ANFIS controller performed a fantastic job of maintaining the power system's frequency deviations within the set limits (figure).6. The controller swiftly compensated for fluctuations in demand and interruptions by adjusting the power output of thermal generators and renewable energy sources, maintaining grid frequency stability. These results showed that the ANFIS controller might lessen the risk of frequency instability by maintaining frequency variations within the proposed operating range. For the two areas' tie-line power flows, the ANFIS controller was important. The controller intelligently responded to variations in tie-line power flows by regulating the output of thermal generators and renewable energy sources, ensuring a consistent regional power exchange. The controller accomplished its goal of controlling tie-line power flows, as shown by the simulation results, which prevented transmission line overloads and underutilization. Results from the transient response analysis confirmed that the ANFIS controller worked well in brief conditions as well. Thermal generators and renewable energy sources may rapidly alter their power production to restore system normalcy after disturbances or changes in demand. In order to keep the grid stable and reliable during transient occurrences,

the simulation proved that the controller can respond fast to changes in the system. The simulation results demonstrated how the ANFIS controller improved AGC performance in two-area power systems. Mixing renewable power with the controller's adaptive and intelligent features improves grid reliability, sustainability, and stability. These findings suggest that AGC systems based on ANFIS are a promising option for future power grid optimisation and integration of renewable energy sources.

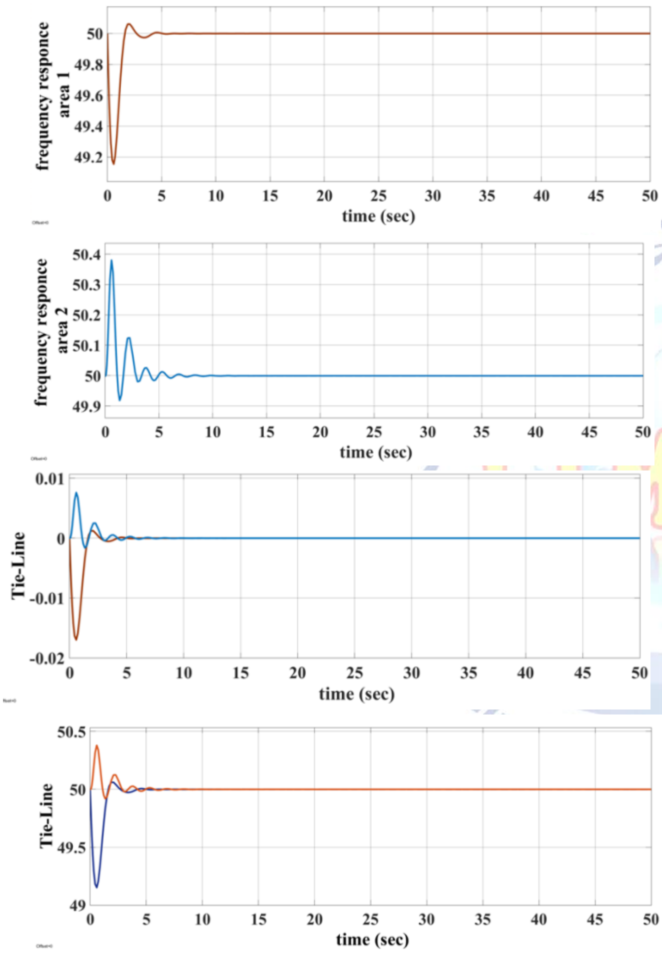


Figure.6 simulation results for ANFIS controller (PI) controller

D. Case: 4 comparative simulation of AGC Performance in Two-Are Power Systems

Figure 7 shows the results of a comparison of the ANFIS, Integral, and Proportional Integral (PI) controllers' performance over a range of operating parameters. By successfully limiting frequency deviations within smaller bounds throughout both sectors of the power system, the ANFIS controller beat the Integral and PI controllers in frequency deviation analysis. Its adaptive and intelligent characteristics improved grid frequency stability by responding faster and making more exact adjustments in the face of unexpected increases in load or disruptions. The ANFIS and Integral controllers did an excellent job of controlling the tie-line power flows that went between the two regions, making sure that the power exchange was balanced. Having said that, the ANFIS controller showed somewhat better performance than the Integral controller when it came to managing tie-line power flows, with less fluctuations. On the other hand, the PI controller proved to be less effective in controlling tie-line power flows, as seen by significantly greater simulation fluctuations.

Performing admirably in the transient response study, the ANFIS controller swiftly restored system balance after load changes or disruptions by adjusting the power output of thermal generators and renewable energy sources. In transient reaction, the Integral controller performed well as well, however it was somewhat slower than the ANFIS controller. The PI controller, on the other hand, showed its shortcomings in dynamic system control with longer reaction times and reduced accuracy in transient situations. When compared to the Integral and PI controllers, the ANFIS controller performed better in reacting to transient situations, controlling frequency deviations, and managing tie-line power flows in the simulations. In two-area power systems, our results demonstrate that AGC systems based on ANFIS improve grid stability, reliability, and performance.

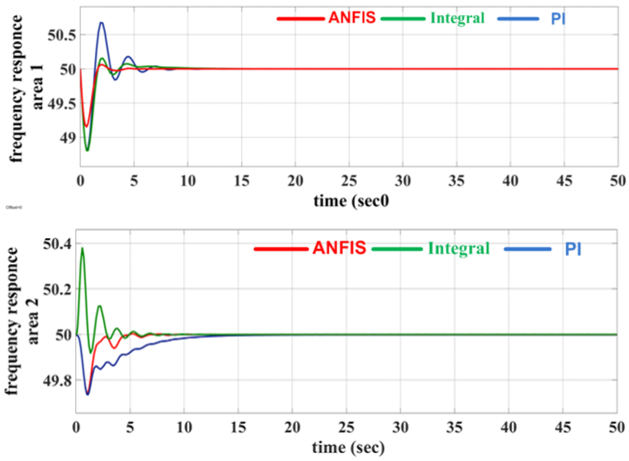


Figure.7 Comparative simulation results for proportional controller (PI), integral, ANFIS controller

VII. CONCLUSION

The Adaptive Neuro-Fuzzy Inference System (ANFIS) controller has been shown to make Automatic Generation Control (AGC) work much better in two-area power systems. This is especially true when using renewable energy sources like solar and wind power. Traditional AGC methods, which rely heavily on PID controllers, struggle to cope with the variability and uncertainty inherent in renewable energy generation. The ANFIS controller, which combines fuzzy logic and neural network capabilities, offers a robust and adaptable solution. It demonstrated superior performance in maintaining system stability, regulating frequency, and managing voltage and reactive power balance under various load conditions and disturbances. The study underscores the potential of intelligent control strategies like ANFIS to support the transition to more sustainable and reliable power systems.

Conflict of interest statement

Authors declare that they do not have any conflict of interest

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